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Automated matching of multiple terrestrial laser scans for stem mapping without the use of artificial references

Jingbin Liu[a,b,*], Xinlian Liang[a,**], Juha Hyyppä[a], Xiaowei Yu[a], Matti Lehtomäki[a], Jiri Pyörälä[a,c], Lingli Zhu[a,**], Yunsheng Wang[a], Ruizhi Chen[b,**]

[a] Department of Remote Sensing and Photogrammetry, Center of Excellence in Laser Scanning Research, Finnish Geospatial Research Institute at the National Land Survey of Finland, 02430, Masala, Finland

[b] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, 430079, Wuhan, China

[c] Department of Forest Sciences, University of Helsinki, 00014, Helsinki, Finland

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ABSTRACT

Terrestrial laser scanning has been widely used to analyze the 3D structure of a forest in detail and to generate data at the level of a reference plot for forest inventories without destructive measurements. Multi-scan terrestrial laser scanning is more commonly applied to collect plot-level data so that all of the stems can be detected and analyzed. However, it is necessary to match the point clouds of multiple scans to yield a point cloud with automated processing. Mismatches between datasets will lead to errors during the processing of multi-scan data. Classic registration methods based on flat surfaces cannot be directly applied in forest environments; therefore, artificial reference objects have conventionally been used to assist with scan matching. The use of artificial references requires additional labor and expertise, as well as greatly increasing the cost. In this study, we present an automated processing method for plot-level stem mapping that matches multiple scans without artificial references. In contrast to previous studies, the registration method developed in this study exploits the natural geometric characteristics among a set of tree stems in a plot and combines the point clouds of multiple scans into a unified coordinate system. Integrating multiple scans improves the overall performance of stem mapping in terms of the correctness of tree detection, as well as the bias and the root-mean-square errors of forest attributes such as diameter at breast height and tree height. In addition, the automated processing method makes stem mapping more reliable and consistent among plots, reduces the costs associated with plot-based stem mapping, and enhances the efficiency.

1. Introduction

Terrestrial laser scanning (TLS) is a technology commonly used for accurate, repeatable, and highly detailed documentation and measurements of three-dimensional (3D) spaces in a variety of applications (Thies et al., 2004; Al-Durgham and Habib, 2014; Zhou et al., 2014; Kelbe, 2015). Placed on a fixed platform or tripod, a laser scanner produces digital representations of the 3D surfaces visible from the scanner. For forest inventories, TLS is often used to record detailed horizontal and vertical forest structures at the plot level (e.g., Thies et al., 2004; Henning and Radtke 2006; Rahlf et al., 2014; Kelbe, 2015). Plot-wise stem mapping is a precise forest inventory technique for generating ground-truthed reference data that is used for calibrating large-scale forest sensing such as airborne laser scanning (ALS) and satellite imagery (Hilker et al., 2012; Wang et al., 2016).

Three data acquisition approaches have been reported for TLS-based forest inventories: single-scan, multi-scan and multi-single-scan (MSS) (Habib et al., 2010; Liang et al., 2016). Among the three approaches, the single-scan approach has the simplest data acquisition setting and the fastest speed. However, single-scan TLS has three challenges in terms of plot-wise stem mapping. First, laser scanning is a discrete sampling technology, and its point density is range-dependent (Jakubowski et al., 2013). These features mean that stems far from the scanner will be mapped at lower detail than those close to the scanner. Second, a single scan can only observe part of a stem; the points of a single scan cover at most half of the lateral section of a stem circle. When these points are used to model

* Corresponding author at: Department of Remote Sensing and Photogrammetry, Center of Excellence in Laser Scanning Research, Finnish Geospatial Research Institute at the National Land Survey of Finland, 02430, Masala, Finland.
** Corresponding authors.
E-mail address: jingbin.liu@nls.fi (J. Liu).

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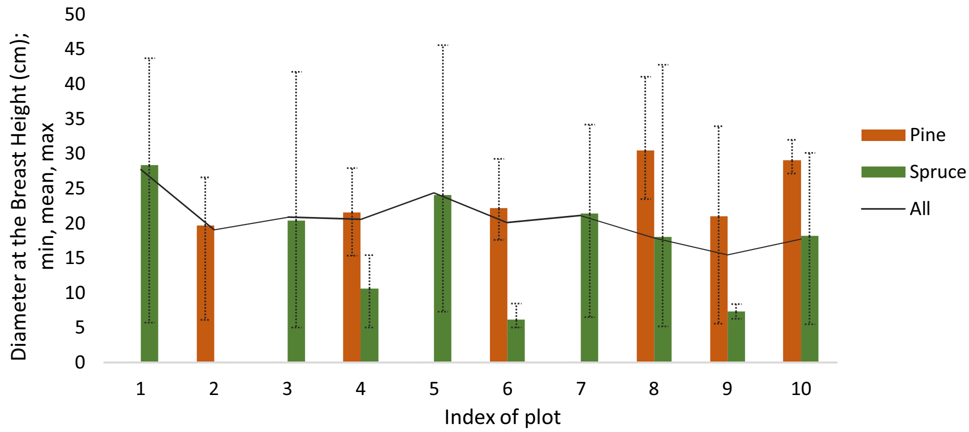

Fig. 1. Minimum, maximum and mean diameter at breast height (DBH, in cm) in each plot. Bars represent the mean DBH for each tree species, with whiskers showing the minimum and maximum values. The line shows the overall mean DBH per plot.

a circular stem, the geometry is unfavorable from a mathematical perspective, which causes errors in the estimation of stem radius and location. Third, natural occlusions limit the visibility of stems inside a plot. Trees may occlude each other; vegetation or terrain in the foreground may also occlude the line of sight to more distant objects. The occlusion effect increases with the distance from the scanner and with the forest density. Studies have shown that up to 40% of all trees in the sample plot are not detectable from the plot center when using the single-scan approach (Lovell et al., 2011). As a result, occluded stem sections or even full stems will fail to be mapped from a single scan. It is necessary to collect multiple scans from different standpoints, and match the point clouds acquired by different scans, so that multiple scans complement each other to attain a complete representation of the 3D scene within a unified reference coordinate system.

A number of automated registration methods have been developed to register multiple scans (Besl and McKay, 1992; Rabbani et al., 2007; Henning and Radtke, 2008; Akca, 2010; Canaz and Habib, 2013; Kelbe, 2015). However, existing automatic registration techniques are usually suitable for engineered surfaces (Glira et al., 2015), and they cannot be directly used to match multiple TLS scans for stem mapping, which is the objective of this study, because of two reasons. First, when a small number of scans are taken, there are typically no adequate overlapping areas that cover tree stems from different standpoints (Liang et al., 2015). Additionally, even when two scans include overlapping view angles, parts of more distant stems may be occluded by closer stems. This occlusion reduces the overlapping area for a specific stem. Second, in the boreal forests where this study was conducted, most stems have a quasi-vertical orientation and similar geometry. In geometry, the correspondence between a pair of parallel cylinders does not provide adequate information for determining translation along their axial direction (Miraliakbari et al., 2008; Al-Durgham and Habib, 2014). Normal vectors, which are often used as geometric features in previous methods, are nearly parallel for most of the stems. As a result, it is difficult to directly estimate the vertical translation between a pair of scans.

In forest inventory, the registration is usually accomplished using artificial reference objects that are placed in a scanning field (Holopainen et al., 2014). The process of manually placing artificial targets in the field and extracting their coordinates from acquired point cloud data strongly depends on the expertise of an operator. For example, field crews must carry the reference objects and tripods throughout field measurements and using them properly requires adequate knowledge (e.g., correctly locating these objects to create a good geometry). These pre-scanning tasks are often labor-intensive and time-consuming, and they greatly increase the cost of data collection. Furthermore, the accuracy and reliability of the registration may be degraded by imprecision or even mistakes during the manual process, even when accomplished by an expert. An automated solution that does not require artificial reference objects would increase the efficiency of fieldwork and post-processing. Such a technique would significantly enhance the applicability of TLS technology in forestry (Liang et al., 2012).

In this study, we present a complete processing procedure for plot-wise stem mapping that is based on automated matching of multiple scans. This automated matching method is developed by exploiting the natural geometric characteristics of trees within a plot, and it does not require the placement of artificial objects in the data acquisition field. This method can be used to match the point clouds of multiple scans within a unified coordinate system. The matched point cloud of multiple scans is then used for plot-wise stem mapping. We compare stem mapping performance using the matched point cloud of multiple scans with that of conventional single-scan based techniques in several respects. The results show that with the proposed method the mean correctness of tree detection in the test plots is improved by 3.1%, and mean stem mapping accuracy is improved by 2.3% to 9.2% for different parameters. More importantly, the proposed method presents in more robust and consistent stem mapping performance among different plots.

2. Study area and materials

2.1. Study area

The study area is a managed forest located near Evo, Finland (61.19°N, 25.11°E). The methods presented in this study were tested with ten plots of 32×32 m. As a reference for the plot attributes, field measurement data were collected in May–July 2014.

All trees with a diameter at breast height (DBH) greater than 5 cm were considered in the reference measurements. The breast height was defined as 1.3 m above the ground level in this study. The main tree species growing in these plots are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). One of the plots is a mixed forest where pine and spruce account for approximately 50% each; the other plots are either pine-dominated or spruce-dominated. The study plots' densities range from 342 to 1191 stems/ha; 70% of the test plots are categorized as high-density based on a threshold number of 600 stems/ha (Watt and Donoghue, 2005).